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Title: Material replacement in quadrupoles of LANSCE DTL tank 1

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Technical Note

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SUBJECT: Material replacement in quadrupoles of LANSCE DTL tank 1.

The fields of short quadrupole magnets in the DTL tank 1 (T1) are calculated with CST EM Studio to evaluate effects of replacing their pole-tip and yoke material: high-purity iron by low-carbon steel. These quadrupoles, the strongest ones in the linac, are embedded into drift tubes, and their replacements may be required to have spare T1 drift tubes available.

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1. Introduction.

This note was initiated by a request [1] to explore what would happen if the yoke and pole pieces in electromagnetic drift-tube quadrupole magnets in the DTL tank 1 (T1) were made of a low-carbon steel instead of their original material, the high-purity (99.85%) ARMCO Ingot Iron [2], which is no longer available. We use the Electro-Magnetic (EM) Studio of the CST Studio Suite to calculate magnetic fields of a model quadrupole for two materials – iron and steel C1008, which is used in electromagnets – to evaluate effects of material replacement.

2. Model.

Details of the linac quadrupoles are described in [2] and illustrated in Fig. 1 below.

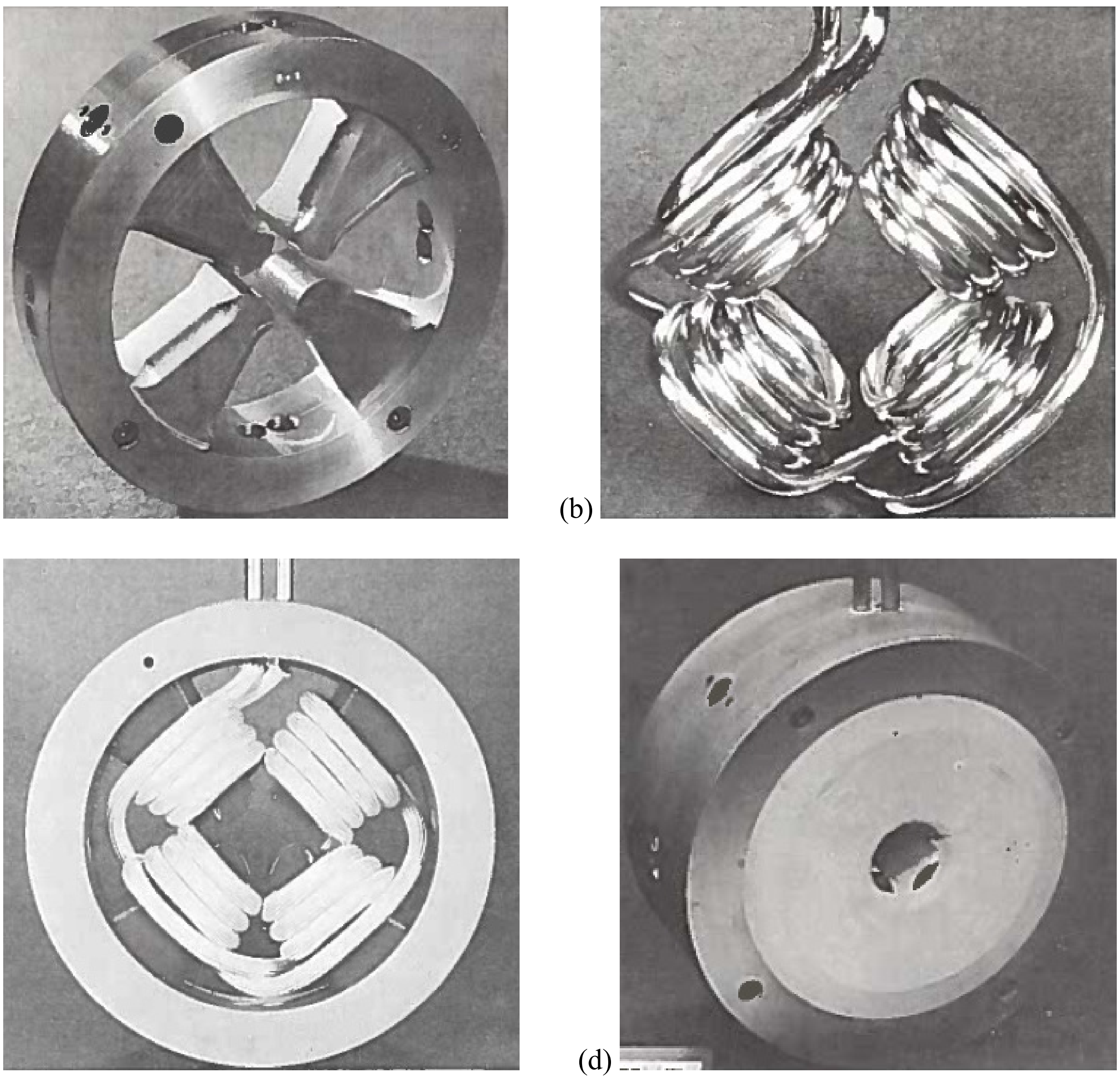

Figure 1: DTL quadrupole details: (a) yoke and pole pieces; (b) current coil; (c) coil assembled with iron; (d) quadrupole fully assembled.

All four quadrupole coils are made out of a single hollow OFHC-copper conductor, with OD d = 7/32" and water-channel ID 1/8", to minimize number of penetrations into the drift tube. There are four turns of the current conductor on each quad pole. The first 6 T1 quadrupoles are very short: the yoke length is 1.030" (2.616 cm) and its outer diameter is 5.75". The bore radius in T1 is 0.75 cm. The initial T1 quad (Q0) is even shorter, 0.678" (1.722 cm), but weaker.

A CAD model of the quadrupole pole pieces and yoke was provided by Elias Pulliam. It was modified to simplify computations, mainly by filling holes in the yoke. This was done to improve the accuracy of field solutions. The adaptive meshing in solving for magnetic fields tends to increase the mesh density near sharp edges (e.g., in holes) to resolve integrable field singularities there, which leads to unnecessary large meshes and longer computation times without improving the accuracy of physically meaningful values. A simplified current coil was also added around the quad pole: its cross section has the height equal to the copper conductor diameter d and the width is $4d$. A quarter of the CST quad model is shown in Fig. 2. The blue lines at the lower left in Fig. 2 show the beam axis ($x = y = 0$) and two displaced axes, ($x = y = 2$ mm) and ($x = y = 4$ mm), where the field components will be plotted.

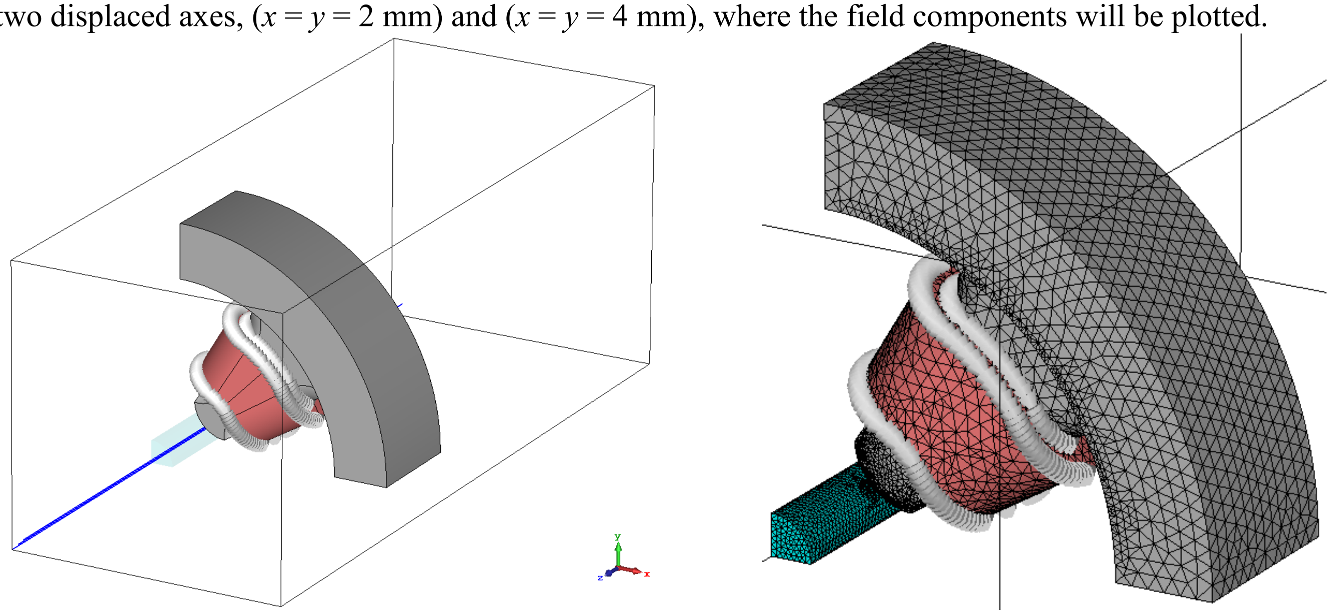

Figure 2: CST model of T1 EM quadrupole: left – one-quarter geometry, magnetic material (grey) and coil (red) and a section of beam aperture where a finer mesh is enforced (light cyan); right – a typical mesh of ~350K tetrahedra after 6 adaptive mesh refinements for 1/8 of geometry.

3. Results.

The quadrupole magnetic field is calculated using the CST model of Fig. 2 with proper boundary conditions (magnetic ones in $x = 0$ and $y = 0$ planes and electric in $z = 0$ symmetry plane) for two magnetic materials and a few different current values. The tetrahedral solver of EM Studio with adaptive meshing is used. The calculated B field is shown in Fig. 3 for a particular case of current 563.37 A, which corresponds in this model to the design value of the quadrupole focusing strength GL_0 = 2.591 T, see below. The maximal field value of 3.29 T seems very high but one can see that it corresponds to locations near the pole sharp edges and is not physical. One can see this more clearly in the right picture of Fig. 3. Elsewhere in the magnetic material the field values are well below 2 T, i.e. below saturation. The same was observed for steel C1008.

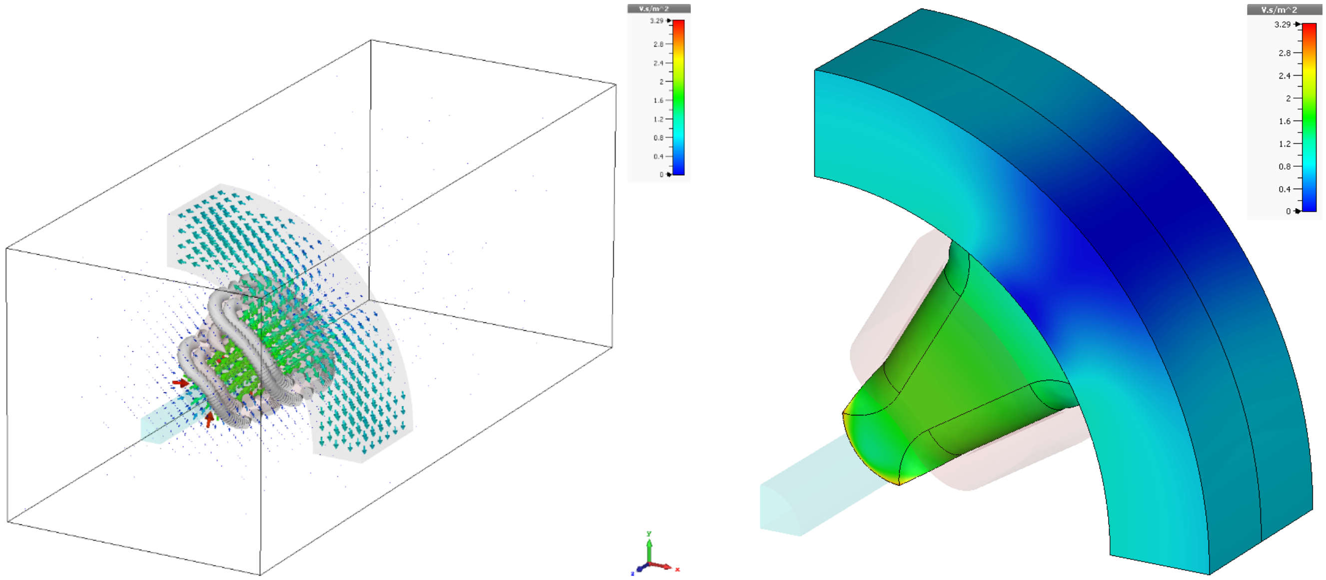

Figure 3: Magnetic field in Q1 with iron: *B*-field arrows (left) and surface magnitude (right).

The transverse field components are integrated along displaced axes (by s = 1 mm and 2 mm in both x and y) to calculate the quadrupole focusing strength GL, gradient G, and effective length L as follows:

$$GL = \int B_x(s,s,z)dz / s, \tag{1}$$

$$G = \max B_x(s,s,z) / s, \tag{2}$$

$$L = GL / G. \tag{3}$$

The design values for the first quadrupole (Q1) in the DTL tank 1 [4] are G_0 = 73.57 T/m and L_0 = 3.522 cm, so that GL_0 = 2.591 T. The Q1 field components along the axis $x = y$ = 2 mm are plotted in Fig. 4.

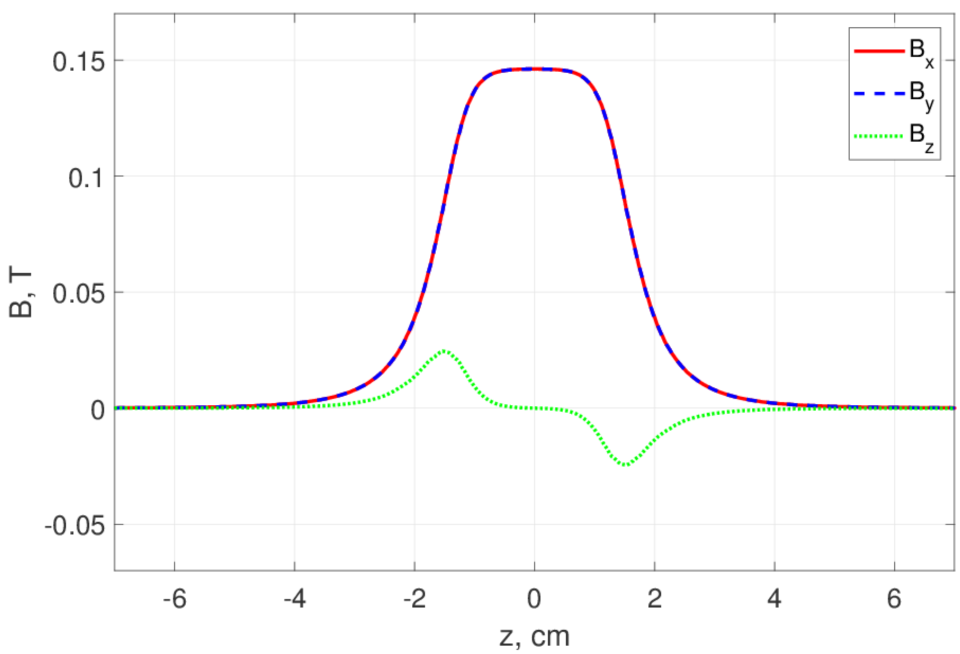

Figure 4: Magnetic field components of quadrupole Q1 along the displaced axis $x = y$ = 2 mm.

The computation results for GL in Q1 with different currents for iron and low-carbon steel C1008 are plotted in Fig. 5.

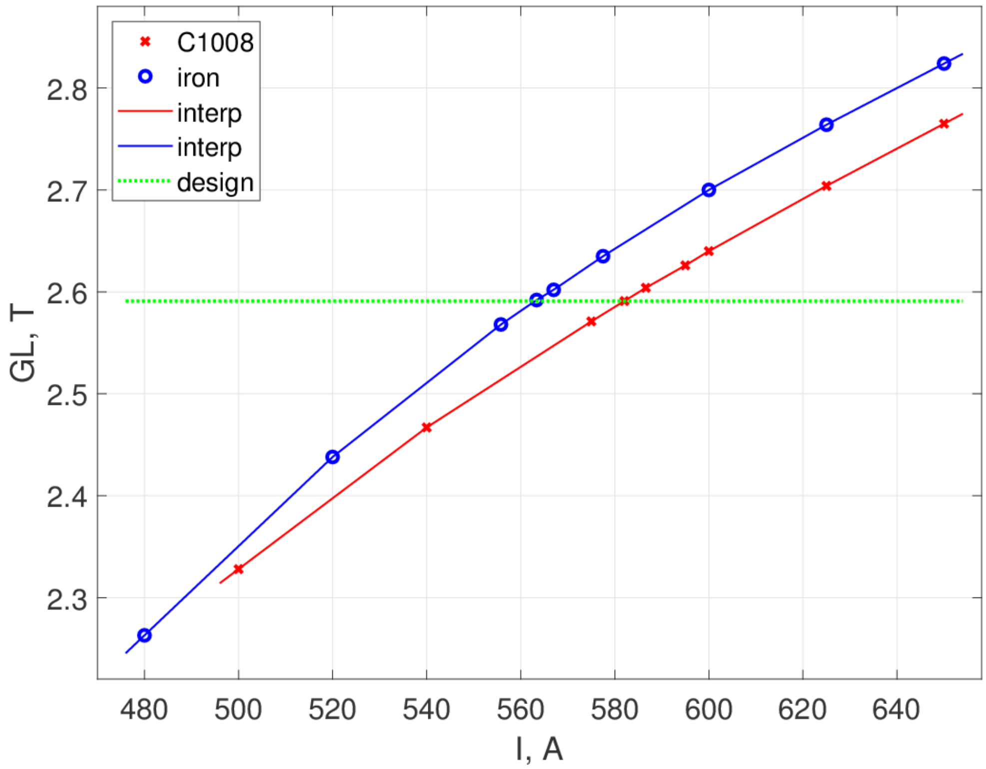

Figure 5: Magnetic strength of quadrupole Q1 vs. current for iron (blue) and steel C1008 (red).

The calculated value of the quad effective length is $L = 3.544$ cm, both with iron and C1008, slightly larger than the design value $L_0 = 3.522$ cm [4]. As we can see from Fig. 5, the design quad strength for Q1, $GL_0 = 2.591$ T, is achieved for C1008 at a larger current than for iron: 582 A vs 563.4 A, i.e. 3.3% higher. This difference is due to different magnetic properties of the two materials: iron has higher magnetic permeability $\mu(H)$ at low values of magnetic field H, and the shapes of $B(H)$ curves are somewhat different near the saturation region, see in Fig. 6, which is extracted from CST EMS data.

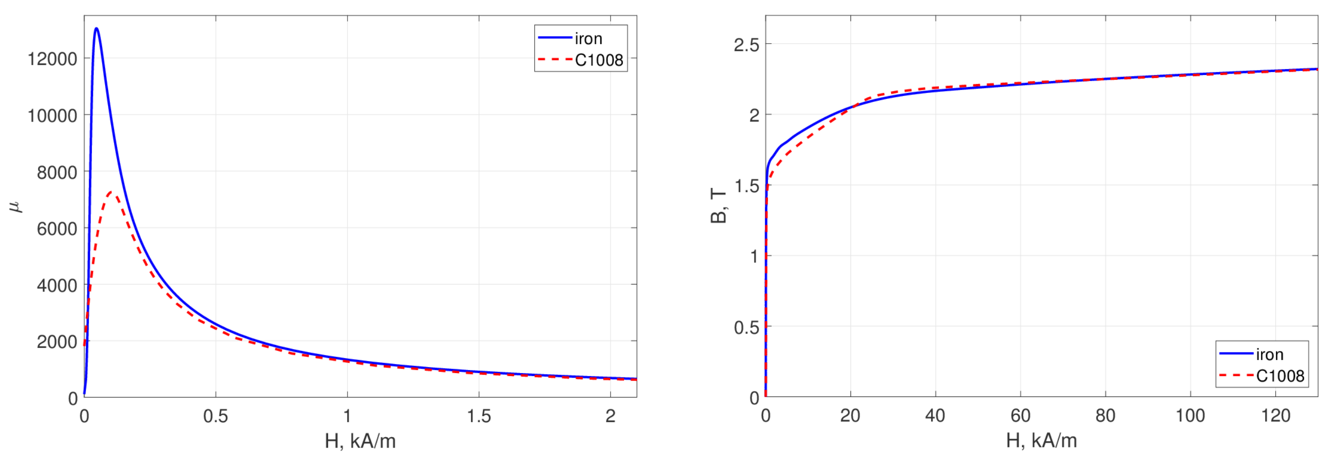

Figure 6: Magnetic properties of iron and steel C1008: permeability (left) and $B(H)$ curves (right).

One should note that though the calculated current values may differ from the ones in real quads, due to our model simplifications, the ratio of currents (steel to iron) is likely less model-dependent. The focusing strengths of the other five short quadrupoles in T1, Q2-6, are lower than in Q1 [4]: $|GL|$ gradually decreases from 2.591 T to 2.44 T. One can see from Fig. 5 that the *GL*-curves for iron and C1008 are getting closer to each other at lower current values, so the currents for Q2-6 will differ by less than 3.3% if iron is replaced by steel C1008 in these quads.

4. Summary.

We calculated the magnetic fields in a simplified model of short quadrupoles in the LANSCE DTL tank 1 (T1) using the CST Electro-Magnetic Studio (EMS) for two materials, iron and steel C1008, to evaluate effects of material replacement in quadrupole yoke and poles. The model is described in Sec. 2. The computation results in Sec. 3 show that the same magnetic field in the first T1 quadrupole (Q1, the strongest quad) will be achieved with the C1008 yoke and poles if the current is increased by 3.3% compared to the existing Q1 quad with iron, cf. Fig. 5. For the following five T1 quads of the same type, Q2-6, the predicted current difference will be less than 3.3%. Of course, the exact current settings for the replacement quadrupoles should be set based on measurements of their magnetic properties. One can also expect similar predictions for other potential replacement materials, like steel C1006, which is more commonly used in electromagnets than C1008.

5. References.

1. W. Barkley and E. Pulliam. Private communication, 08/28/18.
2. E.D. Bush, Jr. "Fabrication of 201.25-MHz Drift-tube Linac Quadrupole Magnets," Report LA-4276, Los Alamos, 1970.
3. CST Studio, www.cst.com
4. http://lansceops.lanl.gov/physics/LinacDB/dtl_tank1.html

Appendix (10/15/18)

The computation results for *GL* in short T1 quadrupoles Q1-Q6 with different currents for iron are plotted in Fig. 7.

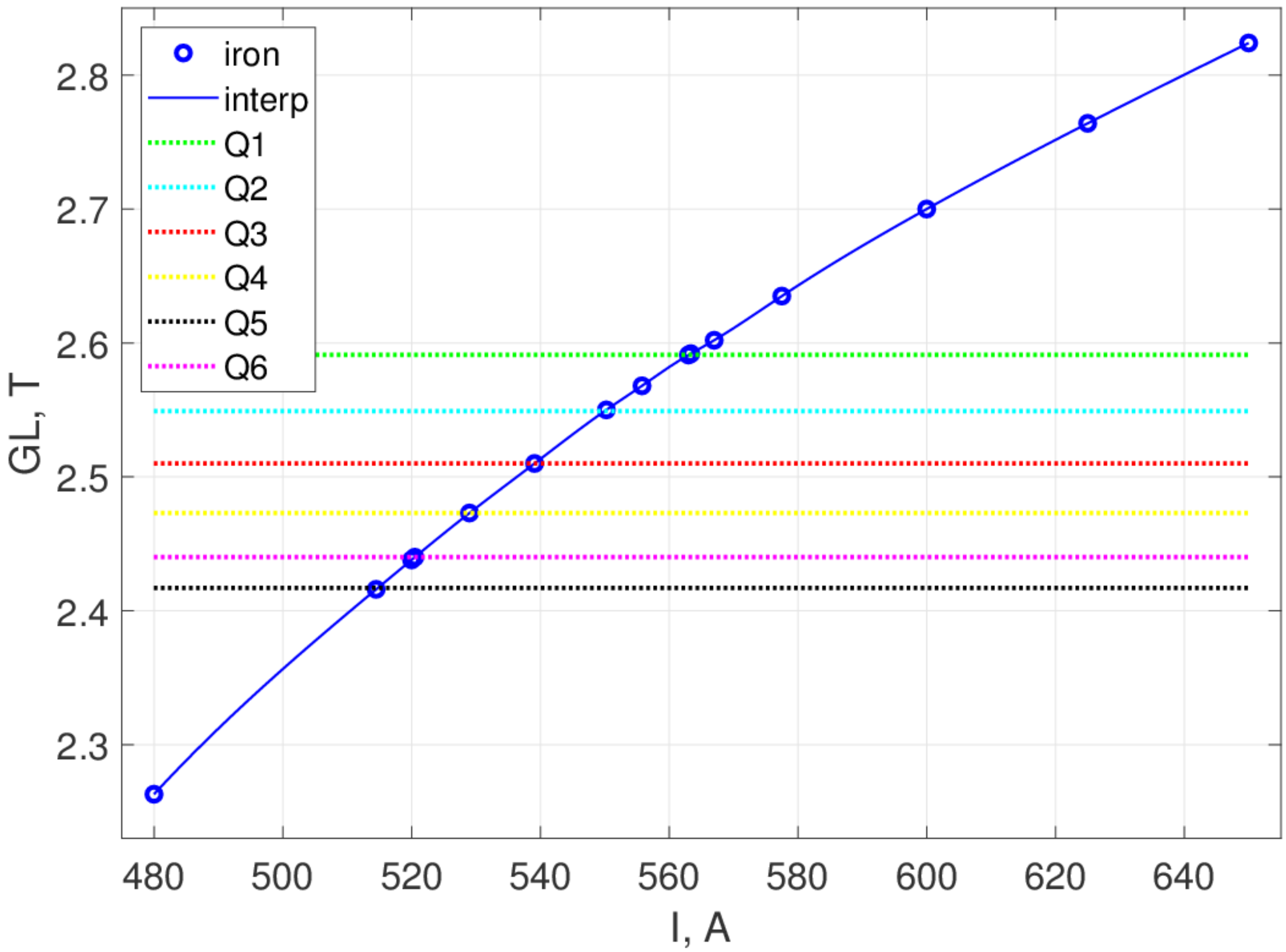

Figure 7: Magnitude of magnetic strength of T1 quadrupoles Q1-Q6 vs. current (blue) and their design strength data (dotted horizontal lines, see legend).

The design focusing strengths [4] for all six short quadrupoles in T1, Q1-6, are plotted in Fig. 7 as horizontal lines. They are lower for Q2-6 than in Q1: $|GL|$ decreases from 2.591 T to 2.416 T in Q5, then becomes slightly larger, 2.44 T, in Q6. The even-number quadrupoles are defocusing, i.e. have negative *GL* values.